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Liquid xenon gamma-ray calorimeter for the MEG experiment

Toshiyuki Iwamoto*

International Center for Elementary Particle Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan

Abstract

The MEG experiment, which searches for a lepton flavor violating muon decay, $\mu \rightarrow e\gamma$, to explore new physics like supersymmetric grand unification, has started physics run since 2008 at Paul Scherrer Institute, Switzerland. Its innovative detector system, which consists of a 900 liter liquid xenon scintillation photon detector with 846 2 inch photomultiplier tubes and a positron spectrometer with a superconducting magnet, drift chamber, and timing counter, enables orders of magnitude better sensitivity than previous experiments.

The liquid xenon gamma-ray detector is a crucial component for our experiment in order to reduce the accidental background and to achieve our goal of sensitivity. Several purification methods including gaseous and liquid phase have been done to increase the scintillation light yield, and various calibration and monitoring methods to evaluate the detector performance have been tried and established. The current performance of the liquid xenon detector for physics analysis and some future prospects are described here as well as the calibration and monitoring methods.

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1. Introduction

$\mu \rightarrow e\gamma$ decay is a lepton flavor violating decay, and is forbidden in the standard model. Even if we take into account tiny neutrino masses, the branching fraction of the decay is expected to be negligibly small ($\sim 10^{-50}$), and we can not reach the level with the present detector technology. The best experimental upper limit of the decay branching fraction before MEG experiment was 1.2×10^{-11} , which was set by MEGA experiment[1].

Then, what is interesting to search for this decay right now is that well motivated new physics like SUSY-GUT, SUSY seesaw etc. predict the branching fraction around $10^{-11} \sim 10^{-14}$ region which is just below the current experimental limit. The MEG experiment will search for this decay mode with a sensitivity of 10^{-13} level, and it means that this experiment has a real chance of discovery of new physics. Even if we do not find any signal, we will set a stringent upper limit which will restrict the current new physics models.

*On behalf of the MEG Collaboration

Email address: iwamoto@icepp.s.u-tokyo.ac.jp (Toshiyuki Iwamoto)

2. Experiment

A proposal of the MEG experiment was approved at Paul Scherrer Institut (PSI) in 1999, and after long time detector R&D work, physics run has been started since 2008 finally. The result of 2008 physics run was already published in [2] in which we set an upper limit of the branching fraction of $\mu \rightarrow e\gamma$ to be 2.8×10^{-11} at 90% C.L. The sensitivity in 2008 was 1.3×10^{-11} , which was already close to the current best upper limit (1.2×10^{-11}). Although there were several major problems in 2008 physics run like drift chamber discharge, lower light yield of liquid xenon etc., all the major problems were fixed before 2009 physics run. Then roughly two months physics run was performed in 2009, and the preliminary result was presented at summer conferences in 2010, which was the branching fraction of upper limit of 1.5×10^{-11} with the sensitivity of 6.1×10^{-12} . Physics run was restarted in 2010, and the obtained 2010 statistics were about twice that of 2009. The combined data in 2009 and 2010 were analyzed, and the result was published in [3] in which we set a 90% C.L. upper limit of 2.4×10^{-12} on the branching ratio of the $\mu \rightarrow e\gamma$ decay, constituting the most stringent limit on the existence of this decay to date. MEG Collaboration consists of about 55 physicists from Japan, Italy, Switzerland, Russia, and USA.

$\mu^+ \rightarrow e^+\gamma$ decay is characterized by a simple two body final state. The positron and gamma are coincident in time, emitted back-to-back in direction, and have an energy equal to half that of muon mass.

There are two major sources of background, one from radiative muon decay (RMD) $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu\gamma$, the other from accidental coincidences between a high energy positron from the normal muon decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ (Michel decay) and a high energy photon from sources such as RMD, positron annihilation-in-flight or bremsstrahlung. In our configuration, the accidental background is the dominant source. In order to reduce this accidental background, the continuous muon beam and precision detectors with excellent spatial, temporal, and energy resolutions are the important things for MEG experiment.

3. Detector

A schematic view of the experiment is shown in Fig.1.

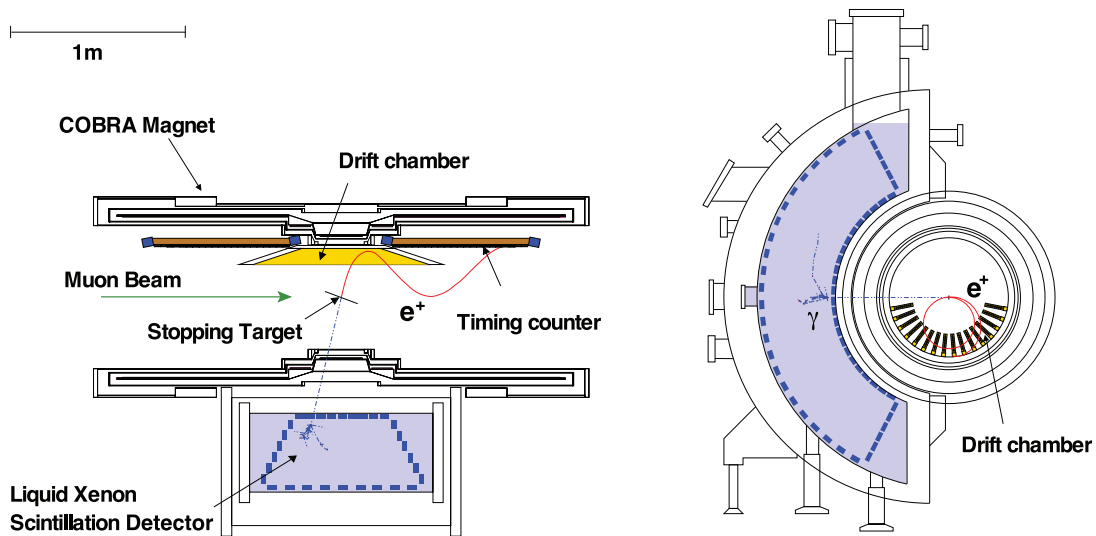


Fig. 1. schematic of the MEG experiment

MEG experiment is composed of mainly three important things, intense muon beam, high precision low mass positron spectrometer with a special gradient magnetic field, and a high performance liquid xenon gamma-ray calorimeter.

There is a 590MeV proton ring cyclotron facility in PSI, Switzerland. Surface muons of 28MeV/c, which originate from pions produced by the interaction of the most intense proton beam with the nuclei of the target material and stopped close to the surface of the target, are used for the MEG experiment. DC muon beam with a rate of $3 \times 10^7 \mu/s$ are stopped in a thin (205 μ m) polyethylene target, placed at the center of the positron spectrometer.

Positron spectrometer consists of superconducting magnet(COBRA, COnstant-Bending-RAdius), drift chamber (DC), and timing counter (TC). The COBRA has a special gradient magnetic field along the beam axis, ranging from 1.27 T at the center to 0.49 T at either end, which is designed such that positrons emitted from the target with the same momenta have an almost constant projected bending radius independent of their emission angle. This allows to sweep away the low momentum positron quickly compared to a uniform magnetic field. The DC consists of 16 radially aligned modules, spaced at 10.5° intervals, which are made of ultra thin materials to reduce multiple scattering of positrons and gamma-ray background production[4]. In order to detect only high momentum positron (>40MeV) and to allow DC operation in high rate environment, DC only covers rather large radius region (19.3cm < r < 27.9cm). The chambers are operated with a helium:ethene (50:50) gas mixture. There is no frame structure at the inner part which faces the target, allowing this low-mass construction to total $2.0 \times 10^{-3} X_0$ along the positron trajectory. Timing information of a positron is reconstructed by means of fast scintillator timing counters, placed at each end of the spectrometer. Each array consists of 15 BC404 plastic scintillator bars with 128 orthogonally placed BCF-20 scintillating fibers. Each bar is read-out at either end by a fine-mesh PMT, while fibers are read-out by APDs. The precise timing and charge information provide both the impact point on TCs and directional information on the positron. Photon detector consists of a 2.7 ton of liquid xenon placed outside of the COBRA whose scintillation lights are detected by 846 PMTs submerged in liquid. This detector will be described in detail in the next section.

4. Liquid xenon detector

4.1. Principle

The photon detector is a homogeneous 900 liter volume of liquid xenon which covers 10% of solid angle, and 846 2 inch PMTs are submerged in liquid in order to detect scintillation light from liquid xenon and to reconstruct energy, position, and timing of gamma-ray. The advantages of using liquid xenon are its high light output, fast timing response, and short radiation length. Its scintillation wavelength is short ($\sim 178nm$), and easily absorbed by impurities such as water and oxygen. In order to remove these impurities efficiently, gaseous and liquid phase purification system has been developed[5]. System diagram of the whole liquid xenon detector is shown in Fig. 2.

A high temperature metal getter is installed in the gaseous purification system, which removes H₂O, O₂, CO, CO₂, H₂, N₂, and CH₄ etc. from gas xenon. Gas xenon is circulated by using diaphragm pump, and the speed is limited by our setup at about 1L/h. Molecular sieves, which remove mainly water, and O₂ getter (which was installed in 2008), which removes electronegative impurities like O₂, are mounted in the liquid purification circuit. Cryogenic centrifugal pump is used to circulate liquid xenon, and the maximum speed is about 100L/h depending on the setup. The detector is controlled at 165K by means of a pulse tube refrigerator with a cooling power of 200W. In order to keep all liquid xenon in a safe way, a liquid xenon storage tank with a volume of 1000L is prepared which has a refrigerator itself[6]. When some maintenance work of liquid xenon detector is done or in emergency or in a winter accelerator shutdown period etc., liquid xenon can be transferred from liquid xenon detector to this storage tank via vacuum-insulated pipe and centrifugal pump.

Energy of incident gamma-ray is reconstructed basically by a weighted sum of all PMTs, position of the first interaction point is estimated from the peak position of light distribution, and timing is estimated from the weighted average of time of PMTs after subtracting time-of-flight. Pileup identification becomes important in high rate environment. Waveforms of all PMTs and light distribution are used for such a purpose. The goal performance of the detector is 1.2-1.5% in energy resolution, 4mm in position resolution, and 65ps in timing resolution.

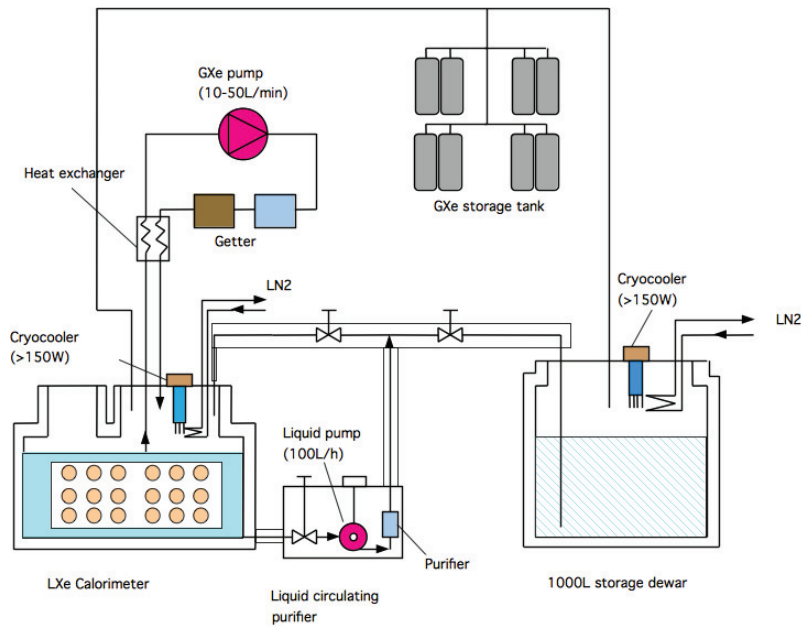


Fig. 2. System diagram of liquid xenon detector

4.2. Calibration & monitor

Various calibration and monitor methods for the liquid xenon detector have been established since 2008. The most important calibration is to use charge exchange (CEX) reaction $\pi^- p \rightarrow \pi^0 n$, $\pi^0 \rightarrow 2\gamma$, and to obtain 55 MeV and 83 MeV almost monochromatic gamma-rays by selecting a back-to-back photon at the opposite side. This 55 MeV is close to our signal energy (52.8 MeV) and is suitable to evaluate our detector performance around signal region. 129 MeV monochromatic gamma-ray can be obtained via $\pi^- p \rightarrow n\gamma$ reactions. Energy, timing, position resolutions as well as probability density functions of gamma-ray for likelihood analysis are evaluated by this calibration. Although it is very powerful calibration, it is difficult to perform this calibration frequently because it takes about two weeks to finish this calibration including preparation time of liquid hydrogen target, π^- beamline, opposite side photon detector (NaI). It is performed once or twice per year.

In order to monitor the detector condition during physics run continuously, 17.6 MeV gamma-ray calibration method by means of $\text{Li}(p,\gamma)\text{Be}$ reaction is established [7]. A Cockcroft-Walton (CW) proton accelerator is installed permanently dedicated for this purpose at downstream side of our beamline, and when we do this calibration, we change the target from usual polyethylene target to a lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$) by using a special bellows insertion system. It can be done rather quickly, and is performed twice or three times per week during physics run.

Neutron generator and nickel plate system is prepared to monitor light yield at 9 MeV produced by neutron capture reaction by nickel plate. This method can be used even in muon beam environment because of the pulse operation of neutron generator. 4.4 MeV gamma-ray is produced by AmBe radioactive source.

Gain of each PMT is evaluated by LEDs and the quantum efficiency etc. is measured by ^{241}Am radioactive sources both of which are installed in the detector. These LED/ α calibrations are performed twice or three times per week together with CW calibration.

4.3. Detector condition

In 2008, it turned out that the light yield of our liquid xenon detector was smaller than the maximum one which is estimated by our prototype detector, and started purification even in physics run. This light yield was monitored by CW calibration, and the constant light yield increase was observed. Since PSI accelerator

has an accelerator shutdown period during winter for maintenance, we continued purification after physics run finished in 2008. We confirmed that the light yield before 2009 physics run is close to the maximum, and we stopped purification during physics run in 2009 and 2010. After all the calibration, the energy scale stability was confirmed to be within 0.2% as shown in Fig. 3.

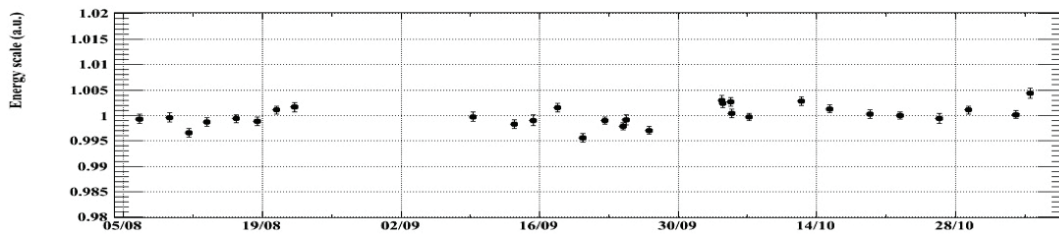


Fig. 3. result of light yield monitoring of 17.6MeV peak position done by Cockcroft-Walton accelerator with Li target.

4.4. Performance

Energy resolution of the gamma-ray detector is evaluated with 55MeV almost monochromatic gamma-rays in CEX. Energy resolution map dependent on the incident positions is measured by moving NaI detector which is placed at the opposite side of the gamma-ray detector. Fig. 4 shows the example of 55MeV energy gamma-ray response in our detector at one position.

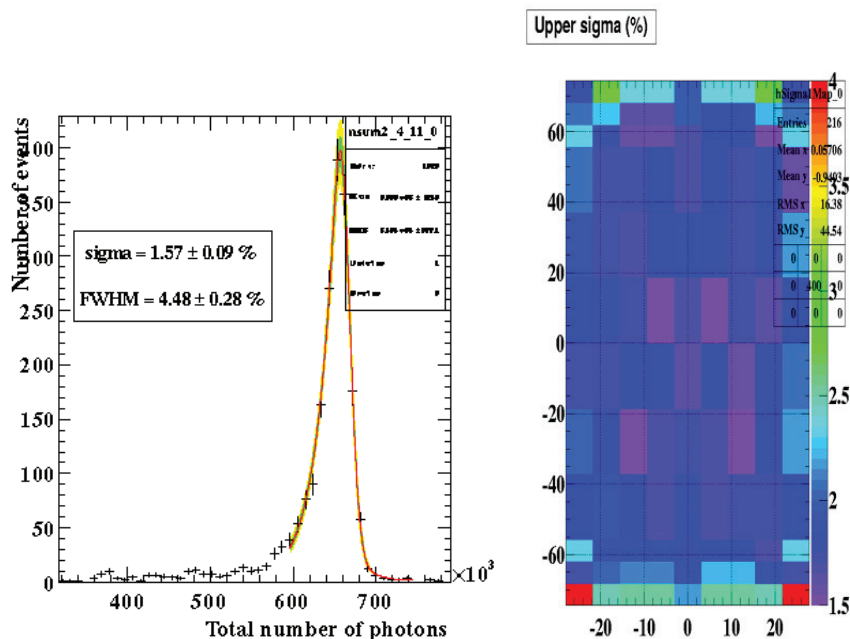


Fig. 4. Left figure: Energy spectrum of 55MeV gamma-rays obtained in liquid xenon detector, and right figure: energy resolution map at different incident position

There is a tail at lower energy region in the left figure of Fig. 4 which is coming from the mainly two reasons. One is the gamma-ray interactions with materials in front of liquid xenon detector, and the other is the shower leakage from gamma-ray incident surface. The whole spectrum is well described by an exponential plus gaussian function. We quote an energy resolution from the sigma of the gaussian. From this

example, we can obtain the energy resolution at 1.57%. Right figure of Fig. 4 shows the energy resolution dependence on different gamma-ray incident positions. One can find about 2% energy resolution at most part, and a slightly worse resolution at the edge part. The typical resolution in 2009 was 2.1% at depth larger than 2cm, 2.8% with depth of 1-2cm, and 3.3% with depth of 0-1cm. Detector linearity can be checked by using gamma-rays between 4.4MeV and 129MeV, and it is confirmed that this detector has a good linearity up to 129MeV.

Position resolution is evaluated also from CEX data where several kinds of lead collimators are put in front of the detector. There are 1cm slits in the collimators, and the events going through the slits are reconstructed, and the position resolution is extracted from the distribution. The obtained position resolution is 5mm for horizontal and vertical axis along incident face, and 6mm at depth direction. The position resolution was measured in 2008 and 2009 in the CEX, and since there was no change observed, the position resolution measurement was skipped in 2010 CEX run.

Timing resolution is measured from the time difference between liquid xenon detector and reference timing counter in CEX run. A special timing counter is prepared for this purpose by plastic scintillator with fine-mesh PMTs in front of NaI detector. The result of the time difference was 119ps at 55MeV, and taking into account the beam spread (58ps) and the resolution of the reference counter (81ps), the timing resolution of the liquid xenon detector is estimated to be 67ps which is close to the goal resolution.

4.5. Background

Gamma-ray background spectrum around signal region in physics run consists of several components, for example, single gamma-ray from radiative muon decay or annihilation in flight, cosmic ray events, and accidental pileup events etc. . Here the cosmic ray event rejection and the pileup event treatment will be discussed, and finally the remaining background spectrum in physics run will be introduced.

Most cosmic ray events have energy more than 100MeV, and are not the main background for us. But some events enter the detector at the edge part, and deposit energy around signal region. Cosmic ray events have different light distribution pattern from signal because most of them enter from the outer part of the detector while the signal events are coming from the inner part faced to the target. We make use of the topological information, namely the charge ratio of the sum of inner and outer faces, $\text{GammaInOutRatio} = (\text{charge sum of inner face}) / (\text{charge sum of outer face})$, and the event depth shown in Fig. 5. Events in left

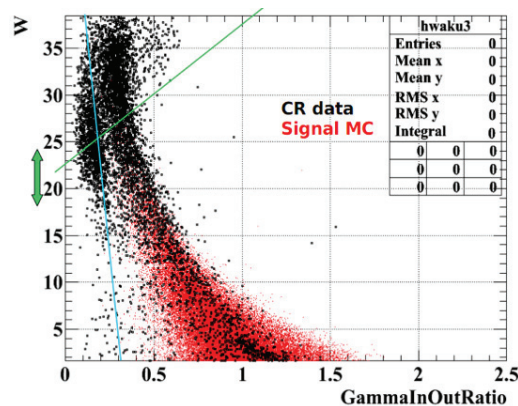


Fig. 5. Distribution of cosmic ray data and signal MC. Horizontal axis shows charge ratio of sum of inner and outer faces which is written as "GammaInOutRatio" in the figure, and vertical axis shows the reconstructed depth of those events. Black points show cosmic ray data and red points show signal MC.

and upper regions separated by two lines are rejected.

There are about 15% pileup gamma-ray events identified in physics run. In order not to lose statistics, we developed an algorithm to eliminate only a gamma-ray with lower energy, and to reconstruct a main gamma-ray. First step is to identify pileup events. There are mainly two kinds of pileup identification methods, one

is to use χ^2 distribution in fitting for timing reconstruction, and the other is to use spacial peak search in PMT charge distribution on the inner and outer faces. If there are two gamma-rays by an accidental pileup in a event, χ^2 value becomes larger. In the present analysis, events with larger χ^2 are rejected. Once we find two peaks spatially separated in inner or outer faces, we try to eliminate one gamma-ray with smaller energy. First, charges of PMTs around a gamma-ray with smaller energy are masked, and the main gamma-ray energy is estimated by fitting method, which compares the data with the template, without those masked PMTs. Then, the charges calculated from the template around the pileup gamma-ray replace the original charges. After that, the usual energy reconstruction is done by the replaced charges. In Fig. 6, two event displays with pileup gamma-ray before and after eliminating the pileup contribution are shown. For safety, we reject those events with energy of pileup gamma larger than 10%.

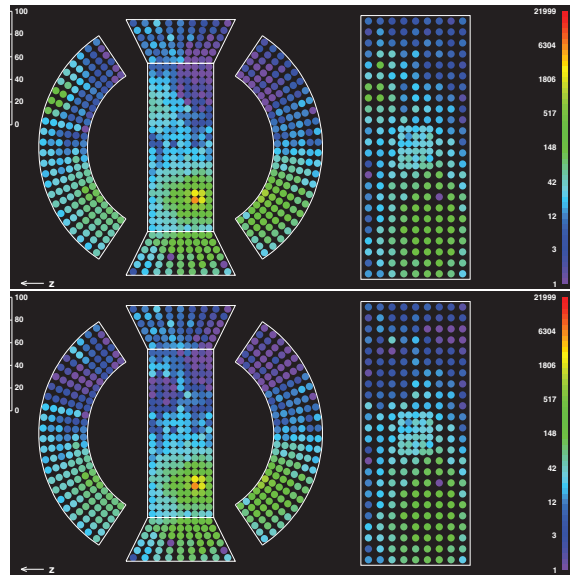


Fig. 6. Before(top figure) and after(bottom figure) eliminating pileup contribution.

After applying cosmic ray rejection and pileup elimination, we can obtain background spectrum from time sideband data in physics run. Fig. 7 shows one example of background spectrum at typical incident position. In order to take into account position dependent gamma-ray background spectra, detector fiducial volume is split into different regions depending on γ incident face and the interaction depth, and each position is treated independently. In order to describe this background shape smoothly, we fit the spectrum with expected distribution. This can reduce a statistical fluctuation at higher energy region. Fitting function is constructed by single gamma energy deposit spectrum in MC of radiative muon decay plus annihilation in flight which are convolved by pedestal data and smeared by detector resolution, and cosmic ray spectrum obtained without muon beam.

As one can see, the background spectrum can be well understood by this method. We can also extract detector performance like energy resolution and energy scale from this fitting, and it is confirmed that those extracted values are well consistent with the calibration data obtained by CEX data. These spectra are used as a probability density function in physics analysis.

5. Status and Prospects

In 2011, full detector calibration run was finished by June, and physics run has been restarted since 30 June, and will be continued until December. MEG experiment will collect more physics data at least in 2011 and 2012 to reach 10^{-13} level sensitivity. In parallel, We are thinking possible improvements about

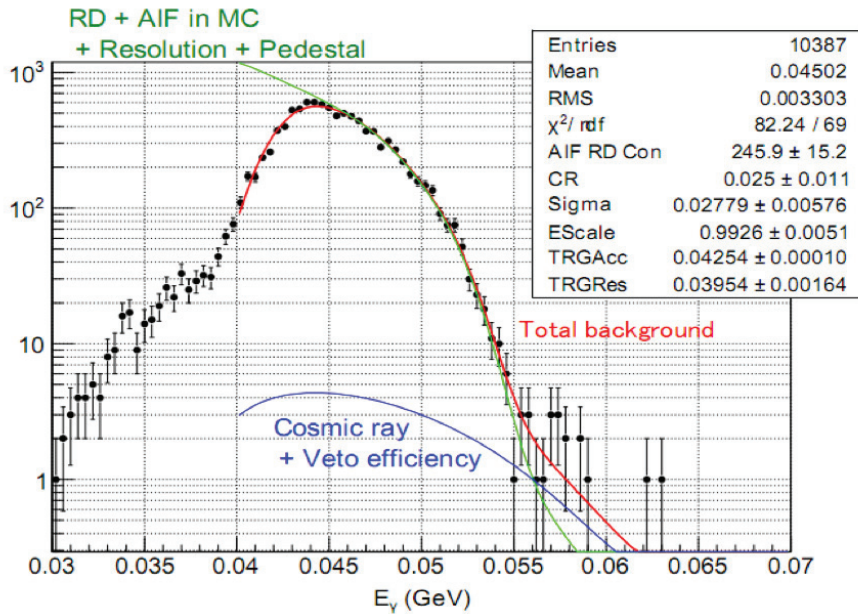


Fig. 7. An example of gamma-ray background spectrum at typical position obtained from a time sideband data in physics run

analysis like improvement of quantum efficiency estimation of each PMT, or new reconstruction algorithm for energy, and about calibration method like stable and better quality data of CEX by using BGO detector instead of NaI detector etc.

6. Summary

Liquid xenon gamma-ray calorimeter has been operated stably and precise calibration methods have been established. High performance has been confirmed, and especially resolutions of timing and position are close to our design values. Important inputs for physics analysis can be extracted by calibration and time sideband data in physics run. We are still trying to improve our detector performance, and we still believe there is room to improve especially energy resolution further.

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